Evidence for magnetic field decay in RX J0720.4-3125

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ABSTRACT

The unidentified X-ray source RX J0720.4-3125 is a candidate isolated neutron star showing evidence for *pulsed* emission with an 8.39 s period and a spectrum consistent with a blackbody at $kT = 80$ eV (Haberl *et al.* 1996, 1997). We show that this source is most likely an old isolated neutron star accreting from surrounding media. We then argue that unless it was born with a long spin period ($P_i \gtrsim 0.5$ seconds) *and* weak field ($B_i \lesssim 10^{10}\,G$), the magnetic field on this star *must* have decayed. With $B_i \sim 10^{12}\,G$, we find decay timescales $\gtrsim 10^7$ yrs for power law decay or $\gtrsim 10^8$ yrs for exponential decay. A measured period derivative $\dot{P} \lesssim 10^{-16}$ s s^{-1} would be consistent with an old accreting isolated neutron star. Both power law and exponential decay models can give a $\dot{P} \sim 10^{-16}$ s s^{-1}, though a $\dot{P}$ substantially less than this would be indicative of exponential field decay.

Subject Headings: pulsars: general — stars: individual (RX J0720.4-3125) — stars: magnetic fields — stars: neutron — X-rays: stars

1. Introduction

There are expected to be $\sim 10^8$-10^9 isolated neutron stars created in the Galaxy since its formation (e.g., Shapiro & Teukolsky 1983). The vast majority of these stars are expected to have spun down from their initial short spin periods and to have long ceased being active pulsars. If, however, they can accrete from surrounding media, they can become visible as sources of soft quasi-thermal X-rays (Shvartsman 1970; Ostriker, Rees, Silk 1970; Treves & Colpi 1991; Blaes & Madau 1993; Madau & Blaes 1994). Compared to the X-ray luminosity, these objects are expected to be very weak in the optical and infrared (i.e., typically $L_X \sim L_{tot} \sim 10^{30}$ erg/s and $L_{opt,IR}/L_X \ll 1$) regardless of whether this emission originates from the stellar surface or from the surrounding photoionized nebula (cf. Blaes & Madau 1993; Blaes et al. 1995). A detection of such old neutron stars would significantly advance our understanding of their spin and magnetic field evolution. The magnetic field evolution of isolated neutron stars is a major unresolved issue in compact object astrophysics. Theoretical studies lead, on the one hand, to exponential (Ostriker & Gunn 1969) or power law (Sang & Chanmugam 1987; Goldreich & Reisenegger 1992; Urpin et al. 1994) forms of field decay, to little or no decay within the age of the universe (Romani 1990; Srinivasan et al. 1990; Goldreich & Reisenegger 1992) on the other. Statistical studies based upon the observed isolated radio pulsars give equally equivocal results (Lyne, Anderson, Salter 1982; Narayan & Ostriker 1990; Sang & Chanmugam 1990; Bhattacharya et al. 1992; Verbunt 1994) owing in large part to the difficulty in treating strong selection effects (e.g., Lamb 1992).

In this paper, we first argue that the soft X-ray source RX J0720.4-3125 is an isolated neutron star accreting from its surroundings. Unlike the two other candidate old neutron stars (cf. Stocke et al. 1995; Walter et al. 1996), this source shows evidence for an 8.39 s rotation period — longer than in any known radio or γ-ray pulsar. From this, we argue that

the magnetic field on this star *must* decay on timescales $\gtrsim 10^7$ yrs if it was born spinning rapidly. A measurement of the period derivative $\dot{P}$ would help test this model.

2. Observations

The source RX J0720.4-3125 is an unidentified soft X-ray source seen by the Einstein IPC (Image Proportional Counter), EXOSAT LE (Low Energy Detector), and, most recently, by the ROSAT PSPC (Position Sensitive Proportional Counter) and HRI (High Resolution Imager). The data on this source is as follows (Haberl et al. 1996, 1997): The ROSAT PSPC count rate (0.1 – 2.4 keV) is 1.6 cts/s, and based upon earlier detections by Einstein and EXOSAT, is steady (no more than $\pm 10\%$ variation) over many years. The X-ray spectrum is best fit by a black body of $kT = 80$ eV with a hydrogen absorption column density of $N_H = 1.3 \times 10^{20}$ cm^{-2}. With this spectrum, the count rate corresponds to an unabsorbed photon energy flux of $F_\nu(0.1 - 2.4 \text{ keV}) \approx 1.7 \times 10^{-11}$ erg/cm^2/s (K. Arnaud, priv. comm.). The source luminosity is then

$$L_X \equiv L(0.1 - 2.4 \text{ keV}) = 1.9 \times 10^{31} d_{100}^2 \text{ erg/s}, \tag{1}$$

where $d = 100 d_{100}$ pc is the distance to the source.

In all pointed ROSAT observations, there is a *periodic* modulation in the X-ray flux with an 8.39 s period (Haberl et al. 1996, 1997). We interpret this as the rotation period of the source. Since the ROSAT observations are separated by ~ 3 years, this indicates that the pulsed emission is steady. Two pointed ROSAT HRI observations (Haberl et al. 1996, 1997) secured the position of the source to be (J2000) α = 7h, 20m, 24.90s; δ =-31° 25′ 51.3″ (with $\pm 3''$ uncertainty). The corresponding Galactic coordinates are $l = 244°$, $b = -8°$. Optical observations at the South African Astronomical Observatory

failed to detect an optical counterpart down to a limiting magnitude of $V \sim 20.7$, thereby placing a lower limit on the X-ray to optical flux ratio of ~ 500 (Haberl et al. 1997).

The observational evidence points consistently to an isolated neutron star as the source.

3. The distance to RX J0720.4-3125

We estimate the distance to the source from the (low) hydrogen column density ($N_H = 1.3 \times 10^{20}$ cm^{-2}). For the first ~ 150 pc, the line of sight to this source cuts through the Local Bubble where the mean hydrogen density is $n_H \sim 0.05$ cm^{-3} (Welsh et al. 1994, their Figure 3). Beyond the Local Bubble, the mean hydrogen density increases substantially to $n_H \sim 0.5$ cm^{-3} near the Galactic plane (Dickey and Lockman 1990). Taking an empty Local Bubble gives a rough upper bound to the distance of about 250 pc.

Given the very nonuniform matter distribution in the local interstellar medium (e.g., Welsh et al. 1994), the actual distance could be much less than 250 pc. For instance, if the source intercepts diffuse cirrus, its distance could be closer to ~ 100 pc (cf. Wang and Yu 1995). A very conservative but strict upper bound on the distance is set by requiring the hot spot area to be much less than the star's surface area for pulsations to be observed. This implies $d_{100} \ll 5.3 R_6$, where $R = 10^6 R_6$ cm is the stellar radius. For definiteness, we adopt 100 pc throughout this work as the source distance and scale our results to this value. Our conclusions regarding magnetic field decay are not sensitive to the distance estimate.

4. Arguments against a young neutron star/pulsar

An active pulsar's spin-down power is (e.g., Shapiro & Teukolsky 1983) $\dot{E}_R = \frac{8\pi^4 B^2 R^6}{3c^3 P^4}$, where B is the dipole magnetic field strength at the polar cap. (We took $\sin\alpha = 1$, where α

is the angle between the rotation axis and magnetic dipole moment [cf. Goldreich & Julian 1969; Verbunt 1994].)

For young radio pulsars (age$\sim$ 10^4–10^6 yrs), $\dot{E}_R \gg L_X$ (cf. eqn [1]; e.g., Ögelman & Finley 1993), yielding $B_{12} \gg 140 d_{100} R_6^{-3} P_{8.39}^2$, where $P = 8.39 P_{8.39}$ s is the current observed pulsar period and $B = 10^{12}\, B_{12}\, G$. This qualifies the source as a "magnetar" (Duncan & Thompson 1992). The spin-down rate is $\dot{P}\Big|_{now}(s\, s^{-1}) = 2.4 \times 10^{-16} \frac{B_{12}^2 R_6^6}{I_{45} P} \gg 6 \times 10^{-13}\, d_{100}^2 P_{8.39}^3 I_{45}^{-1}$, where $I = 10^{45} I_{45}$ g-cm^2 is the star's moment of inertia. The consequent young spin down age — $\tau_{sp} = \frac{P}{2\dot{P}} \ll 2.2 \times 10^5\, d_{100}^{-2} P_{8.39}^{-2} I_{45}$ yrs — and close proximity ($\sim$ 100 pc) argues against a young neutron star/pulsar origin. This object lies well above the (extrapolated) observed radio pulsar death line ($B_{12} > 15 P_{8.39}^2$; e.g., Chanmugam 1992). Adopting L_{radio} (mJy-kpc^2) $= 4 \times 10^6\, \dot{P}^{1/3}/P$ (cf. Narayan & Ostriker 1990) yields a radio luminosity at 400 MHz of $L_{400} \sim 4300\, d_{100}^{-4/3} I_{45}^{-1/3}$ mJy. Unless our line-of-sight falls outside its radio beam (J. Cordes, priv. comm.), then even given the large spread (up to a factor of 100) in the actual radio luminosities about the best-fit $L_{radio}(P, \dot{P})$ (e.g., Lamb 1992), such a bright and *persistent* radio pulsar should have already been detected (cf. Taylor, Manchester, Lyne 1993). The absence of radio emission further argues against a young neutron star/pulsar origin.

If the source is a Geminga-type (γ-ray loud, radio-quiet) pulsar, then $\dot{E}_R \sim L_\gamma \gg L_X$. Adopting $L_\gamma / L_X \sim 10^3$ as for Geminga (Halpern & Holt 1992; Swanenburg et al. 1981; Thompson et al. 1977) yields $\tau_{sp} \sim 200$ yrs, which argues against a Geminga-type pulsar. This is consistent with lack of detection by EGRET instruments aboard the Compton Gamma-Ray Observatory (Haberl et al. 1997).

5. Accreting old neutron star and field decay

If the source is an isolated neutron star accreting from the surrounding medium, its mass accretion rate will be governed by the rate at which material is captured within the star's gravitational radius $r_g = \frac{2GM}{V^2} = 9.3 \times 10^{13}\, M_{1.4} V_{20}^{-2}$ cm, and is given by (cf. Bondi 1952) $\dot{M}_{11} = 1.3 M_{1.4}^2 n_H V_{20}^{-3} f_{acc}$, where $\dot{M} = 10^{11} \dot{M}_{11}$ g/s, $M = 1.4 M_{1.4} M_\odot$ is the stellar mass, n_H is the hydrogen number density of the medium (assumed to have solar abundance), $V = (v^2 + c_s^2)^{1/2} = 20 V_{20}$ km/s with v being the star's speed relative to the ambient medium, c_s being the sound speed in the ambient medium, and f_{acc} is a factor that accounts for the microphysics of the accretion process. If the accretion is adiabatic, $f_{acc} \sim 1$ (Bondi-Hoyle accretion). If preheating of the incident flow is important, f_{acc} could be much less than unity (Shvartsman 1970; Ostriker et al. 1976; Blaes, et al. 1995; Wang & Sutherland 1997). Combining eqn (1) for L_{tot} and $L_{tot} = GM\dot{M}/R$ gives $V_{20} = 1.1 f_{acc}^{1/3} n_H^{1/3} d_{100}^{-2/3}$. Taking $c_s \sim 10$ km/s then gives $v \lesssim 2c_s$, that is, a slowly moving neutron star. In this case, accretion occurs in a quasi-spherical manner near the star (i.e., for $r_g \gg r \gg$ Alfvén radius [see below]; cf. Hunt 1971). The condition $v > 0$ also gives another distance constraint; $d_{100} < 3.3 f_{acc}^{1/2} n_H^{1/2}$, with the upper limit corresponding to $v = 0$.

For material to reach the surface of the rotating magnetized star, the star must have spun down sufficiently so that accreting material can overcome the centrifugal barrier (cf. Illarionov & Sunyaev 1975). The neutron star's spin evolution is divided into three phases (see, e.g., Blaes & Madau 1993; Lipunov, Postnov, & Prokhorov 1997). In the first (dipole) phase, the star is an active pulsar and spins down by magnetic dipole radiation; $-\dot{\Omega} = -\dot{\Omega}_{dip} = \frac{B^2 R^6 \Omega^3}{6 I c^3} = 6.2 \times 10^{-18} R_6^6 I_{45}^{-1} B_{12}(t)^2 \Omega(t)^3$ (s^{-2}), where $\Omega = 2\pi/P$ is the star's angular velocity. This phase ends when the ram pressure of the ambient material ($\sim \rho V^2$) overcomes the pulsar wind pressure ($\sim \dot{E}_R/(c 4\pi r^2)$) at $\sim r_g$ so that matter can now enter the star's magnetosphere. This happens when the star's period

$P > P_0 \equiv 4.4 M_{1.4}^{-1/2} R_6^{3/2} v_{20}^{1/2} n_H^{-1/4} B_{12}^{1/2}$, s. In this second (propeller) phase, material enters the corotating magnetosphere and is stopped at $\sim r_A$, the Alfvénic radius, where the energy density in the accretion flow balances the local magnetic pressure. This radius is given by $r_A = 1.5 \times 10^{10} f_{acc}^{-2/7} n_H^{-2/7} V_{20}^{6/7} M_{1.4}^{-5/7} \mu_{30}^{4/7}$ cm, where $\mu = BR^3/2 = 10^{30}\mu_{30}$ G-cm^3 is the neutron star's magnetic moment.

Further penetration cannot occur owing to the centrifugal barrier, that is, $r_A > r_{co}$ (cf. Illarionov & Sunyaev 1975), where $r_{co} = \left(\frac{GM}{\Omega^2}\right)^{1/3} = 6.9 \times 10^8 M_{1.4}^{1/3} P_{8.39}^{2/3}$ cm is the corotation radius. Since the accretion is quasi-spherical, material falls in initially with negative total energy (material is bound) and roughly zero angular momentum.

Spin down in this phase occurs via propeller and magnetic dipole spin-down; $\dot{\Omega} = \dot{\Omega}_{prop} + \dot{\Omega}_{dip}$. If the infalling material cools efficiently and attaches itself to field lines at around r_A, the star expels the material once it spins up the material to the local escape velocity at $\sim r_A$. By angular momentum conservation, $-\dot{\Omega}_{prop}^{l} \sim \frac{\dot{M}(2GMr_A)^{1/2}}{I} = 2.5 \times 10^{-16} M_{1.4}^{15/7} R_6^{6/7} I_{45}^{-1} f_{acc}^{6/7} n_H^{6/7} V_{20}^{-18/7} B_{12}(t)^{2/7}$ (s^{-2}). If the material does not cool and/or thread the field lines efficiently, the hot gas will remain bound in a "cocoon" at $\sim r_A$. As the underlying magnetosphere rotates supersonically shearing through this "cocoon," the consequent shock heating expels material from the star (Illarionov & Sunyaev 1975). By energy conservation, $-\dot{\Omega}_{prop}^{e} \sim \frac{GM\dot{M}}{I\Omega r_A} = \frac{1}{\sqrt{2}}\left(\frac{r_{co}}{r_A}\right)^{3/2} \dot{\Omega}_{prop}^{l} \sim 10^{-2}\dot{\Omega}_{prop}^{l}$, where the final expression is typical for a star just entering the propeller phase. In this limit, only a fraction of the energy given to escaping material goes into azimuthal motion, so $-\dot{\Omega}_{prop}^{e} \ll -\dot{\Omega}_{prop}^{l}$. We therefore take $\dot{\Omega}_{prop} = f_p \dot{\Omega}_{prop}^{l}$, where $0.01 \lesssim f_p \lesssim 1$ is taken as a freely adjustable parameter. The exact value of f_p requires time-dependent numerical simulations (e.g., Wang & Robertson 1985). If $f_p \sim 1$, $\dot{\Omega}_{prop} \gg \dot{\Omega}_{dip}$ throughout this phase.

Propeller action continues until $r_A < r_{co}$, when the centrifugal barrier is removed and polar cap accretion ensues (e.g., Lamb et al. 1973; Davidson & Ostriker 1973; Arons & Lea

1980). This occurs when $P > P_a \equiv 470 M_{1.4}^{-11/7} R_6^{18/7} f_{acc}^{-3/7} n_H^{-3/7} V_{20}^{9/7} B_{12}^{6/7}$ s. In quasi-spherical accretion, no net *torque* is exerted on the star (due to accretion). The mass loading of the field lines, however, now becomes important in spinning down the star by increasing the moment of inertia of the star + corotating magnetosphere system [1] (see, e.g., Mestel 1990 for a discussion of this effect in normal stars). For $r_A \gg R$, angular momentum conservation ($\frac{d}{dt}(I\Omega) = 0$) gives $-\dot{\Omega}_{brk} = \frac{\dot{I}}{I}\,\Omega \sim \frac{\dot{M} r_A^2}{M R^2}\,\Omega = 4.5 \times 10^{-15}\, M_{1.4}^{-3/7} R_6^{10/7} n_H^{3/7} V_{20}^{-9/7} f_{acc}^{3/7}\, B_{12}^{8/7}\,\Omega$ (s^{-2}). (In the limit of a weakly magnetized star where $r_A < R$, $r_A \to R$ in the above expression and $-\dot{\Omega}_{brk} \to \frac{\dot{M}}{M}\,\Omega$.) The total spin-down rate in this final (accretion) phase is then $\dot{\Omega} = \dot{\Omega}_{brk} + \dot{\Omega}_{dip}$, although, quite generally, $\dot{\Omega}_{brk} \gg \dot{\Omega}_{dip}$.

For accretion to occur, we require $r_A < r_{co}$, that is, $P > P_a$. For pulsed emission, that is, polar cap accretion, we require $r_A \gg R$. Combining these, the present day surface field must satisfy

$$10^{-7}\, M_{1.4}^{5/4} R_6^{-5/4} V_{20}^{-3/2} n_H^{1/2} f_{acc}^{1/2} \ll B_{12} < B_{crit,12} \equiv 9.3 \times 10^{-3} M_{1.4}^{11/6} R_6^{-3} f_{acc}^{1/2} V_{20}^{-3/2} n_H^{1/2} P_{8.39}^{7/6}. \tag{2}$$

This condition rules out the possibility of measuring the field directly through cyclotron (emission) line observations, which require $B_{12} \sim 1$ (Nelson et al. 1995).

Assume first that the star's field does not decay, that is, its initial field B_i is the same as the current field and satisfies eqn (2). We obtain an upper bound to the period P_0 by using $B < B_{crit}$ (cf. eqn [2]);

$$P_0 < P_{crit} \equiv 0.42 M_{1.4}^{5/12} f_{acc}^{1/4} V_{20}^{-1/4}\ \mathrm{s}. \tag{3}$$

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[1] I thank Eve Ostriker for pointing out the potential importance of this effect.

If the star was born with $P_i < P_0 < P_{crit}$, it must first dipole spin down to P_0. This takes $t_{dip,0} = 6.3 \times 10^7\, P_0^2 B_{12}^{-2} R_6^{-6} I_{45}$ yrs $> 1.3 \times 10^{11}\, M_{1.4}^{-17/6} I_{45} P_{8.39}^{-7/6} n_H^{-1} V_{20}^{5/2}$ yrs, where we have used $B < B_{crit}$ (cf. eqn [2]) to arrive at the inequality. The star thus spends longer than a Hubble time ($\sim 10^{10}$ yrs) just in the first (dipole) phase.

If the star was born with $P_0 < P_i < P_{crit}$, it goes directly to the second (propeller) phase. Propeller spin down to P_a takes $t_{prop,a} = 1.1 \times 10^9\, f_p^{-1}\, M_{1.4}^{-15/7} R_6^{-6/7} I_{45} f_{acc}^{-6/7} n_H^{-6/7} V_{20}^{18/7} B_{12}^{-2/7} \left(\frac{1}{P_i} - \frac{1}{P_a}\right)$ yrs $>$ $10^{10}\, f_p^{-1}\, M_{1.4}^{-37/12} I_{45} n_H^{-1} f_{acc}^{-5/4} V_{20}^{13/4} P_{8.39}^{-1/3}$ yrs, where we have used $B < B_{crit}$ (cf. eqn [2]), $P_i < P_{crit}$ (cf. eqn [3]), and $P_i \ll P_a$ to arrive at the inequality. The star thus spends longer than a Hubble time in this phase. (If $f_p \ll 1$, magnetic dipole spin down will be important initially, but propeller spin down dominates eventually.)

We conclude that if the star was born with $P_i \lesssim P_{crit} = 0.42 M_{1.4}^{5/12} f_{acc}^{1/4} V_{20}^{-1/4}$ s, then to enable sufficient spin down to allow accretion onto the star, it *must* have been born with a stronger field than at present, that is, *the stellar magnetic field must have decayed*.

Of course, if the neutron star is born slowly rotating, i.e, with $P_i \gg P_{crit}$, then the star can spin down within a Hubble time to 8.39 s without requiring magnetic field decay. However, it is unclear how neutron stars can form with such long initial spin periods *and* weak magnetic fields (cf. eqn [2]). One possibility is that RX J0720.4-3125 actually evolved from a high mass X-ray binary system (cf. Haberl et al. 1997). [2] We argue here, however, that conventional isolated neutron star models can account quite well for the properties of RX J0720.4-3125.

In general, the star's spin and magnetic field history is determined by P_i, B_i, the field

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[2]It is also possible that no accretion is involved and that RX J0720.4-3125 is powered instead by some internal heat source (see, e.g., Thompson & Duncan 1996).

decay law, and decay timescale t_d. The dependence on P_i, however, is very weak whenever $P_i \ll P_a$, which is generally believed to be the case (e.g., Narayan & Ostriker 1990).

In Figure 1, we illustrate sample evolutionary tracks in B-P space for two magnetic field decay laws. For the solid curve, the stellar field is assumed to decay as a power law, i.e., $B(t) = B_i/(1 + t/t_d)$ (e.g., Narayan & Ostriker 1990; Sang & Chanmugam 1987), with $t_d = 3.8 \times 10^7$ yrs. For the dot-dashed curve, exponential decay is assumed, i.e., $B(t) = B_i \exp(-t/t_d)$ (e.g., Ostriker & Gunn 1969), with $t_d = 4 \times 10^8$ yrs. To construct these tracks, an isolated neutron star with $M = 1.4 M_\odot$ and $R = 10$ km is assumed to be born with $P_i = 0.01$ s $< P_{crit}$, $B_i = 10^{12}\,G$, and is assumed to be moving at 20 km/s through a medium with $n_H = 1$ cm^{-3} and $c_s = 10$ km/s. Spin down spans the magnetic dipole, propeller, and accretion phases. For the propeller spin down rate, we took $f_p = 1$ and for the accretion rate, we took $f_{acc} = 1$. In the power law decay model, the star enters the accretion phase at 5.7×10^9 yrs and spins down to 8.39 s in 6.2×10^9 yrs. For the exponential decay model, these numbers are 1.9×10^9 yrs and 2.1×10^9 yrs, respectively.

For $B_{i,12} \sim 1$, we find $t_d \gtrsim 10^7$ yrs for power law decay models (cf. Urpin et al. 1994), while $t_d \gtrsim 10^8$ yrs for exponential decay models. These results are consistent with several recent analyses of pulsar statistics and field decay (e.g., Wakatsuki et al. 1992; Bhattacharya et al. 1992; Lamb 1992; Urpin et al. 1994; Verbunt 1994), and with the analysis assuming power law decay in Narayan & Ostriker (1990). For $B_{i,12} \lesssim 0.1$, the star cannot enter the accretion phase within a Hubble time even for the most favorable case of a stationary ($v = 0$) star. If $f_p \ll 1$, the star will not be able to enter the accretion phase *and* spin down to 8.39 s in a Hubble time unless $v \ll 20$ km/s (cf. Blaes & Madau 1993).

From $\dot{\Omega}_{brk}$ and $B < B_{crit}$ (cf. eqn [2]), we obtain an upper bound to the current spin down rate;

$$\dot{P}\Big|_{NOW} < 1.8 \times 10^{-16}\, M_{1.4}^{5/3} R_6^{-2} n_H V_{20}^{-3} f_{acc} P_{8.39}^{7/3} \quad (\mathrm{s\,s^{-1}}). \tag{4}$$

In both models shown in Figure 1, the 8.39 s period is reached shortly after the star enters the accretion phase, and $\dot{P}|_{NOW} \approx 10^{-16}$ s s^{-1}.

It is evident from Figure 1 that P in the exponential decay model asymptotes after entering the accretion phase while P for the power law decay model continues to increase monotonically. This is because in exponential decay models, the field, and hence r_A (lever arm) decreases more rapidly at late times, whereas the field in power law decay models persists longer. If neutron star fields undergo exponential decay and the 8.39 s period in RX J0720.4-3125 is the star's asymptotic period, then we expect $\dot{P}|_{NOW} \ll 10^{-16}$ s s^{-1}.

We have so far assumed that the stellar magnetic field decays indefinitely. We emphasize, however, that once the stellar field has decayed sufficiently to enable accretion (cf. eqn [2]), no further decay is required by the observations. Thus, for instance, the decaying field may level out at late times to a steady finite long-lived value (e.g., Kulkarni 1986; Romani 1990).

6. Conclusions

We argue in this paper that RX J0720.4-3125 is an old isolated neutron star, situated at $\sim$ 100 pc, that has spun down long past the active pulsar stage and is now accreting matter from the interstellar medium. Unless the star was born with an unusually long period ($P_i \gtrsim 0.5$ s; cf. eqn [3]) *and* weak magnetic field ($B_i \lesssim 10^{10}\,G$; cf. eqn [2]), such spin down is only possible if the star's field at birth was much stronger than at present, that is, the star's field *must* have decayed. Our analysis gives long decay timescales; $\gtrsim 10^7$ yrs for power law decay and $\gtrsim 10^8$ yrs for exponential decay, assuming $B_i \sim 10^{12}\,G$.

A $\dot{P} \lesssim 10^{-16}\,\mathrm{s\,s^{-1}}$ would be consistent with an old accreting isolated neutron star. Both power law and exponential decay models can give a $\dot{P} \sim 10^{-16}\,\mathrm{s\,s^{-1}}$. A $\dot{P} \ll 10^{-16}\,\mathrm{s\,s^{-1}}$, however, would be indicative of exponential field decay. In addition, an accreting isolated neutron star should be surrounded by an extended photoionized nebula (cf. Shvartsman 1971; Blaes & Madau 1993; Blaes et al. 1995). This low surface brightness nebula should be dominated by $H\alpha$ in a compact inner zone ($\sim 10^{17}$ cm; e.g., Blaes et al. 1995) and be rich in mid to far infrared metal forbidden lines (e.g., [NeII]12.8μ, [SiII]35μ) in an extended outer zone ($\sim 10^{18}$ cm). The results of deep spectroscopy can therefore be used as an additional test of the model presented here.

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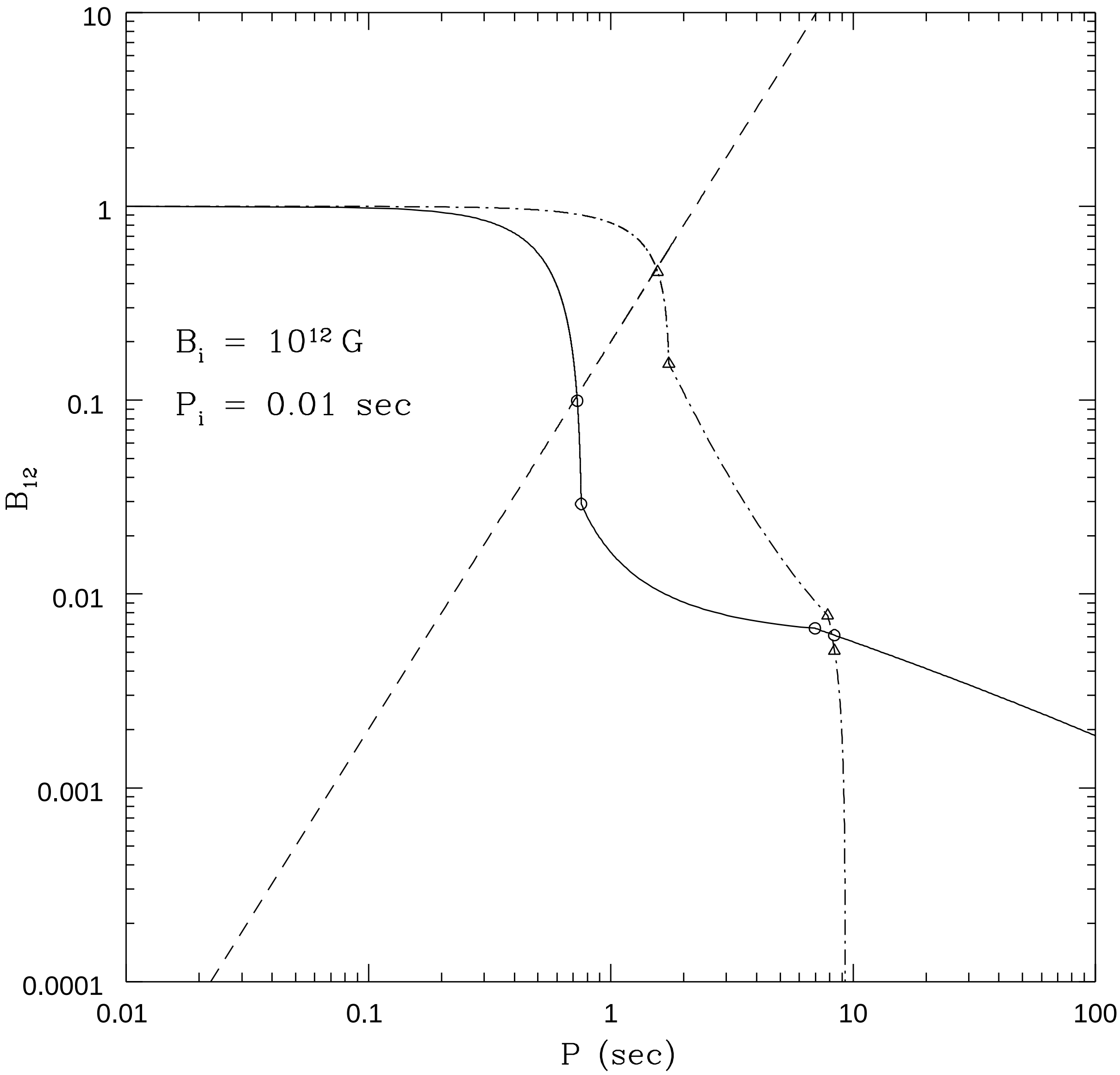
Fig. 1.— The spin period and magnetic field evolutionary track for a neutron star ($M = 1.4\,M_\odot$, $R = 10$ km) born with period $P_i = 0.01$ s and surface dipole field strength $B_i = 10^{12}\,G$. The star is assumed to be moving at $v = 20$ km/s through a medium (solar abundance) with density $n_H = 1$ cm^{-3} and $c_s = 10$ km/s. The star's field undergoes (solid curve) power law decay ($B(t) = B_i/(1+t/t_d)$) with $t_d = 3.8\times10^7$ yrs, or (dot-dashed curve) exponential decay ($B(t) = B_i\exp(-t/t_d)$) with $t_d = 4\times10^8$ yrs. Dashed line gives the observed radio pulsar death line ($B_{12} = 0.2P^2$). For power law decay, the star drops below the death line at $t \approx 3.5\times10^8$ yrs after its birth when $P = 0.73$ s. Propeller spindown begins at $t \approx 1.3\times10^9$ yrs when $P = P_0 = 0.76$ s. The star enters the accretion phase at $t \approx 5.7\times10^9$ yrs when $P = 6.96$ s. Spin down to the observed 8.39 s period occurs after 6.2×10^9 yrs. For exponential decay, the corresponding times and periods are (3.1×10^8 yrs, 1.56 s), (7.5×10^8 yrs, 1.74 s), (1.9×10^9 yrs, 7.86 s), and (2.1×10^9 yrs, 8.39 s), respectively. Each of these events is marked with an open circle on the curve for the power law decay model (solid) and an open triangle on the curve for the exponential decay model (dot-dash).



B_i = 10^{12} G
P_i = 0.01 sec
B_{12}
P (sec)
10
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
100